Mesoscopic capacitor effect in GaN/AlGaN quantum wells

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The recent developments in the field of GaN-based blue-UV optoelectronic devices have stimulated several experimental and theoretical studies on GaN/AlGaN MQWs. Most of the attention has been paid to the existence of built-in electric fields in such heterostructures [1-2]. Several experiments have indeed shown that the ground level emission of narrow GaN/AlGaN QWs falls below the energy gap of the bulk GaN [3-6]. Though this is a confirmation of the presence of an internal electric field, there is still a quantitative disagreement between the experimental ground level energy deduced by the optical experiments and that obtained by the envelope function theory with the inclusion of built-in electric fields. In this work we present a new approach to the problem, which is based on the idea that the GaN quantum wells behave like mesoscopic capacitors. The GaN/AlGaN QWs investigated in this study were fabricated by metal organic chemical vapour deposition (MOCVD) on sapphire substrates, and carefully characterized from the structural point of view by X-ray diffraction, Rutherford back scattering and high resolution Secondary Ion Mass Spectroscopy (Fig.1). The structural characterization was a fundamental step of this work, since it allowed us to perform a quantitative analysis of the optical spectra without uncontrolled structural parameters (namely, well width and composition profile), to be used in the theoretical model. We demonstrate that the ground level energy is influenced by two main effects: *(i)* the charge accumulation in the well, caused by the separation of the wavefunctions and by the increase of the radiative recombination time induced by the built-in field, and *(ii)* the loss of carriers from the ground level induced by the non-radiative recombination processes. The first effect (the mesoscopic capacitor effect) leads to the built-up of an electron-hole plasma in the well which screens the built-in field (resulting in a screening induced blue shift of the luminescence which partly compensates the red shift induced by the built-in field), and it becomes more and more important in wide wells by virtue of the increased decay time (wavefunction separation) causing the charge accumulation at the interfaces. The second effect, partly compensates the charge accumulation and causes the recovery of the built-infield value expected for zero charge density. The proper account of these phenomena provides a new insight in the coupling of GaN/AlGaN structures with light, which has both fundamental and applied relevance. A self consistent model including the mesoscopic capacitor effect reproduces quantitatively the well width dependence of the ground level emission with the inclusion of strain, built-in field, charge accumulation, radiative and non radiative terms, without free parameters (continuous line through the data in Fig 2). We show that in wide wells, the increase of the wavefunction separation and of the electron-hole pair lifetime induced by the built-in field enhances the mesoscopic capacitor effect, resulting in a charge accumulation which screens the built-in field. This causes a blue shift of the ground level energy with respect to the unscreened built-in field case. Concomitantly, the non-radiative recombination processes cause a depletion of the quantized states, which partly balances the capacitor effect, inducing a partial recovery of the unscreened bult-in field (i.e. a red shift of the ground level). Therefore the competition between radiative and non-radiative recombination determines the well width dependence of the ground level energy, through the well width dependent mesoscopic capacitor effect. Our results are summarized in Fig. 2, for three different values of the non radiative time constant.

References

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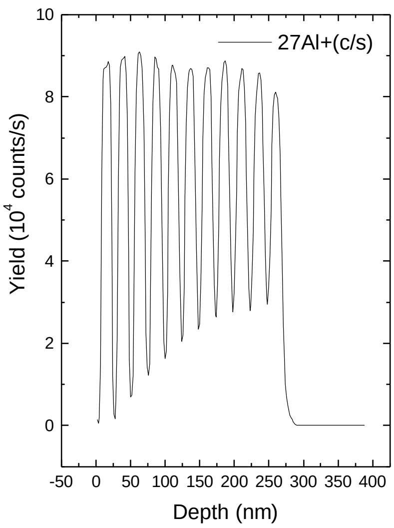

Fig 1

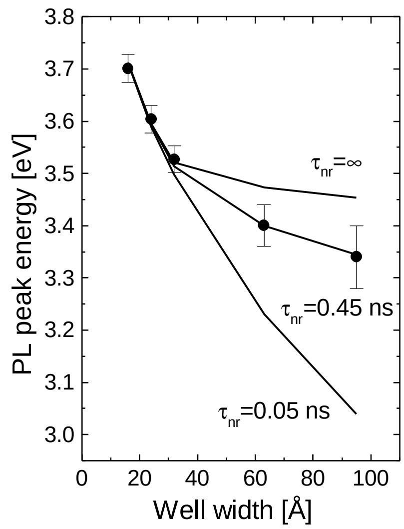

Fig 2

Fig 1. Secondary Ions Mass Spectroscopy profile of the sample 5, using a 1.6 keV O_2^+ ions primary beam and detecting the secondary 27Al+ ions emitted from the samples as a function of depth.

Fig 2. Experimental (circles) and theoretical values (lines) of the emission energy of the samples. The theoretical calculations are performed using three different values of the non radiative lifetime τ_{nr}: 0.5 ps, 0.6 ns and ∞.